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Settling Velocity, Aggregate Stability, and Interrill Erodibility of Soils Varying in Clay Mineralogy

José Miguel Reichert
Federal Univ. of Santa Maria
97105-900 Santa Maria
RS Brazil

L. Darrell Norton*
USDA-ARS
National Soil Erosion Research Lab.
275 S. Russell St.
Purdue Univ.
West Lafayette, IN 47907-1196

Nerilde Favaretto
Federal Univ. of Paraná
Curitiba
PR, Brazil

Chi-hua Huang
USDA-ARS
National Soil Erosion Research Lab.
275 S. Russell St.
Purdue Univ.
West Lafayette, IN 47907-1196

Elena Blume
Federal Univ. of Santa Maria
97105-900 Santa Maria
RS Brazil

Mechanisms of aggregate disruption and the measurement techniques used to quantify them for different aggregate sizes affect the relation of aggregate stability to soil erodibility and to basic soil properties. We evaluated two different techniques of aggregate stability analysis that gave either a settling velocity or stability of aggregates parameter for different sized aggregates which we compared with interrill erodibility for 10 clay soils. We compared the differences in these parameters from slow wetting to reduce slaking to air-dried aggregates and compared these differences to soil properties. Aggregate settling velocity and stability and soil interrill erodibility were strongly affected by clay mineralogy and physical–chemical properties. The mechanism of aggregate disruption was dependent on clay type. Slaking during fast wetting was important in kaolinitic/oxidic soils, whereas highly smectitic clay increased particle dispersion and slaking on swelling, with a consequent reduction in size and speed of settling aggregates. Swelling of clays may have overridden any reduction in slaking by slow capillary prewetting of illite or smectite (with no kaolinite) soils, causing aggregate instability with both slow and fast wetting procedures. Correlation analysis showed that 4.76- to 8-mm aggregates with a high slaking index also demonstrated more slaking under wet sieving and slower fall velocity. Interrill erodibility had greater correlation with the mean weight diameter (MWD) of stable aggregates in the 1- to 2-mm size class, than for the whole soil (aggregates < 8 mm), and no correlation was observed with any of the slaking indexes involving wet sieving or settling in water. Multiple regression analysis indicated that 89% of the variability in erodibility for prewetted soil was explained by MWD of prewetted 1- to 2-mm stable aggregates (MWD_W), available water content, and fall velocity of 1- to 2-mm dry aggregates, while 96% of the variability in erodibility for dry soil was explained by MWD_W for 1- to 2-mm prewetted aggregates, water dispersible clay, and fall velocity for 1- to 2-mm dry aggregates. The interrill erodibility, for dry and wet soil, was greatest for the highly smectitic and least for the high-clay kaolinitic/oxidic, both under annual crops. The higher erodibility and lack of slaking reduction effect on our prewetted soil under simulated rainfall is explained by a confounding effect of high water table, high steady-state runoff and slaking.

Abbreviations: ASI, aggregate stability index; CEC, cation exchange capacity; D, air-dry soil; *D* for dry sieved; K_i, interrill erodibility; KR, erodibility ratio; MWD, mean weight diameter; SI_{AS}, slaking index based on aggregate stability; SI_V, slaking index based on settling velocity; V_{50}, fall velocity; W, prewetted soil; *W* for wet sieved.

The most prevalent procedure to test aggregate stability is the wet sieving with the mean weight diameter (MWD) index for expressing the size distribution of aggregates. However, according to Lovell and Rose (1988b), aggregate settling velocity is a better measure of structural stability which in some cases presents more advantages than aggregate-size distribution measured by wet sieving. For example, in studies involving sediment transport and deposition, settling velocity of soil aggregates becomes an essential tool, and it is a function of several properties including size, density, shape, and moisture content of the aggregates or of particles (Lovell and Rose, 1988a, 1988b).

Organic matter, clay, and oxide contents are the soil properties normally associated with aggregate stability (Kemper and Koch, 1966). Soil organic matter is thought to increase aggregate stability by lowering the wetability and increasing the cohesion of aggregates (Chenu et al., 2000), and the life-time of aggregates is dependent on its size (Puget et al., 2000). Different kinds of organic matter stabilize aggregates of different sizes (Tisdall and Oades, 1982), and organic matter may have no effect on swelling soils (Coughlan et al., 1973).

Clay mineralogy also plays an important role in aggregation, but an increase in clay does not always result in increased stability. Soil mineralogy has substantial effects on clay dispersion, thus influencing aggregate stability, runoff, and soil loss (Lado and Ben-Hur, 2004). The stability of high-clay soils depends on the physical-chemical properties of the clay (Warkentin, 1982). Variable charge clay minerals (1:1 clays and oxides) have a greater potential to form stable aggregates when organic concentrations are low, while with additional organic inputs soils with mixed mineralogy have the greatest response in stable macro-aggregate

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*Corresponding author (norton@purdue.edu).

Table 1. Classification, sampling location, texture, and many clay minerals of the studied soils.

Soil Series	Classification	Texture of sampled soil (A or Ap horizon)	Sampling location	Land use	Main clay minerals
Bayamón	Typic Haplorthox	Clay	Puerto Rico- USA	Cropland	kaolinite, goethite
Cecil eroded	Typic Hapludult	Clay	Georgia- USA	Cropland	kaolinite, HIV
Grey Clay	Udic Chromustert	Clay	Queensland- Australia	Cropland	smectite, kaolinite
Heiden	Udic Chromustert	Silty Clay	Texas- USA	Cropland	smectite, calcite
Hoytville	Mollic Ochraqualf	Clay	Ohio- USA	Cropland	illite, vermiculite
Irving Clay	Typic Pellustert	Clay	Queensland- Australia	Cropland	smectite
Londrina	Rhodic Haplorthox	Clay	Paraná- Brazil	Cropland	kaolinite, hydroxy-interlayered vermiculite, gibbsite
Middle Ridge	Typic Haplorthox	Clay	Queensland- Australia	Cropland	kaolinite
Molokai	Typic Eutrotorrox	Clay	Hawaii- USA	Cropland	kaolinite
Pierre	Ustertic Cambiorthid	Clay Loam	South Dakota- USA	Cropland	smectite, illite

formation (Denef et al., 2002). Illitic and kaolinitic soils with small amount of smectite may be dispersible and as susceptible to sealing as smectitic soils (Stern et al., 1991) since smectitic clays are generally more dispersive than kaolinitic clays (Goldberg and Glaubig, 1987) and have lower aggregate stability (Wakindiki and Ben-Hur, 2002).

Some soils have strong aggregation which is usually attributed to the presence of free Al or Fe compounds (Six et al., 2000), but may not necessarily play a role in aggregation since remobilization of Fe during soil formation is essential for Fe forms to play a role in aggregation, such as in Oxisols (Muggler et al., 1999). Amorphous Fe is more effective than crystalline forms at stabilizing soil aggregates, even though it is present in lower concentrations (Duiker et al., 2003). Soil mineralogy dominated by 1:1 clay minerals and oxides in tropical regions is associated with a higher aggregate stability, but a lower correlation between C contents and aggregate stability is observed (Six et al., 2002).

Initial water content, rate of wetting, size class, and the method of determination are also determinants of aggregate stability and erosion (Truman and Bradford, 1990; Truman et al., 1990; Le Bissonnais, 1996; Levy et al., 1997; Reichert and Norton, 1994b). Prewetting at low tensions increases aggregate stability (Bullock et al., 1988), but if rapid wetting occurs differential swelling and air compression may cause incipient failure or slaking of aggregates, coupled with the weakening of interparticle forces. Lovell and Rose (1988b) observed that rapid wetting of the air-dry sediment caused a general decrease in aggregate settling velocities and attributed this to the breakdown of the coarser aggregates, predominantly by slaking. Aggregate slaking occurs due to disruption of aggregates by pressure buildup of entrapped air in the inter-particle spaces of the aggregate (Le Bissonnais, 1990, 1996).

Different mechanisms responsible for aggregation (Tisdall and Oades, 1982) affect diversely the stability of different soil fractions (Truman and Bradford, 1990; Zhang and Horn, 2001). Zhang and Horn (2001) observed that the mechanism of aggregate breakdown was in the order, slaking > mechanical breakdown > microcracking and they differed with soil type and composition. These distinct mechanisms of aggregate disruption of different aggregate sizes and the measurement techniques used to quantify them should affect the relation of aggregate stability to soil erodibility and to basic soil properties.

Aggregate stability by wet sieving is a well-established method and is more related to soil management effect on soil structure. Another technique to determine aggregate stability is based on high energy moisture characteristic (Levy and Mamedov, 2002), which produces information on low tension water retention, plus infiltration and surface seal potential. Conversely, methods based on settling velocity, such as the one proposed by Hairsine and McTainsh (1986), generate direct information on aggregate slaking, sediment transportability, and speed of deposition.

In spite of the importance of soil aggregation and its relation to soil erosion, information on the effects of measurable soil properties on interrill erodibility, particularly for clayey soils with varying mineralogy, is limited. This research hypothesized that aggregate settling velocity and stability and soil interrill erodibility are dependent on clay mineralogy, where disruption of aggregates is mainly the result of slaking during fast wetting in kaolinitic/oxidic soils, and particle dispersion and slaking on swelling in highly smectitic soils. The specific objectives of this study were to: (i) determine the effect of antecedent moisture on settling velocity and stability of aggregates from some clayey soils with varying clay mineralogy, (ii) evaluate soil interrill erodibility for these soils under air-dried (D) and slowly prewetted (W) conditions, and (iii) identify relationships between interrill erodibility and aggregate and soil properties.

MATERIALS AND METHODS

Soil samples were taken from A horizons (0–10 cm) from 10 soils from Australia, Brazil, and USA. Soil samples were collected at field moisture, air-dried, and gently sieved through an 8-mm sieve before shipping them to the National Soil Erosion Research Laboratory at Purdue University. Predrying and sieving was necessary since several samples were collected overseas, avoiding the need of rewetting bulk samples which would invariably dry and harden during shiping. All soils had high clay content (302–662 g kg^{-1}), which originated from a variety of climatic and pedogenic environments. Soil classification, clay mineralogy, and textural classes are given in Table 1, whereas a more detailed physical and chemical characterization is presented in Table 2 and methods used can be found in Reichert and Norton (1994a, 1996).

Settling velocity of three size classes (<8.00 D, 1.00- to 2.00-mm D, and 4.75 to 8.00 D and W) were determined in triplicate by using a Griffith tube. The tube is a 2-m long glass tube with a closed top where aggregates can be placed into a free standing column of water either dry or in solution. The tube is much like holding your finger over a straw and lifting it out of water full except much larger. The bottom of the water column is open and the material falling can be collected at the bottom as of function of travel time. This material is dried and the mass determined and related to the average time from the beginning of collection until collection stops. Several samples up to 20 can be collected to create a fall velocity mass distribution versus fall time in meters per second (m s^{-1}). The apparatus, procedure, and calculations are fully described in Hairsine and McTainsh (1986), whereas applications are presented in Loch (2001). The fall velocity at 50% mass (V_{50}) was calculated by regression.

The MWD of stable aggregates was determined in triplicate by wet sieving (MWD_W) (Kemper and Rosenau, 1986) of both air-dried (MWD_{WD}) and prewetted aggregates (MWD_{WW}) for three size classes: <8.00-mm, 4.75- to 8.00-mm, and 1.00- to 2.00-mm aggregates. The MWD of air-dried aggregates <8 mm was also determined by dry sieving (MWD_{DD}), whose size distribution characterizes the soil samples used for settling velocity, wet sieving, and erodibility studies. Air-drying was at room temperature under fairly humid conditions so the drying was not rapid, whereas the prewetting of the aggregates for both the Griffith tube and wet sieving analyses was done by gradual wetting at −0.5-kPa matric potential with deionized water for 2 h. Deionized water was used as a surrogate for rainfall water, which is also very low in electrolytes, having similar effects in terms of clay dispersion and electrolyte leaching.

Since the slaking of aggregates is due to aggregate disruption caused by entrapped air during rapid wetting (Le Bissonnais, 1996), by comparing slow and fast-wetting results two slaking indices were defined. One slaking index is based on settling velocity (SI_V) and was defined as the ratio between the V_{50} of prewetted soil (V_{50W}) to the V_{50} of air-dry soil (V_{50D}) (Norton and Dontsova, 1998; Green et al., 2004). Another index is based on aggregate size (SI_{AS}) was obtained by dividing the MWD_{WW} by MWD_{WD} of each aggregate-size class. Both indexes, as defined herein, describe the difference between the disintegration of air-dried aggregates by rapid wetting and the disintegration of prewetting aggregates by differential swelling mostly (Le Bissonnais, 1996).

The ratio of MWD from wet and dry aggregate by size fraction allows comparing soils with different initial aggregate-size distribution Thus, for soil with aggregates <8-mm prewetted under tension, an aggregate stability index (ASI) was obtained by dividing $MWD_{WW<8}$ by $MWD_{DD<8}$. The ASI can be used to quantify the increase in mean aggregate size due the reduction in the examined aggregate breakdown process.

Interrill erodibility (K_i) was calculated using erosion data from Reichert and Norton (1994a, 1996), following Elliot et al. (1989). For these erosion trials, a 3-cm layer of sieved-soil with aggregates <8 mm was packed over a 12-cm sand layer in a 32-cm wide and 45-cm long erosion pan. The erosion pans were designed to only capture surface runoff and infiltrating water was sampled from below under a slight tension (−5 cm). More details of the erosion pan are given in Bradford and Ferris (1987).

Before the rain, the soil was either (i) prewetted from the bottom with deionized water and left saturated for a total of 2 h; then the slope was set to 5%, and let drain for 30 min at −0.5 kPa matric potential; or (ii) kept air-dried. We expected less structural collapse, maintaining porosity, and thus less change in hydraulic properties with prewetting. During the rain, the slope of the erosion pan for both treatments was at 5% and a −0.5 kPa matric potential was kept on the prewetted treatment.

Constant rainfall at a target rate of 110 mm h^{-1} was applied using a programmable rain simulator equipped with 80–100

Table 2. Selected physical and chemical properties of the studied soils.†

Soil	Sand	Silt	Clay CDC	Clay WDC	pH H_2O	pH $CaCl_2$	OC	Exchangeable cations Na	Exchangeable cations Ca	Exchangeable cations TB	CEC	BS	ESP	SAR	Fe_d	Al_d	Fe_o	PZSE	SA	COLE	θ_g at -33 kPa	θ_g at -1500kPa	Flocculation CFC	Flocculation pH ‡
	g kg^{-1}						g kg^{-1}	$cmol_c$ kg^{-1}				%			g kg^{-1}				m^2 g^{-1}	cm cm^{-1}	g kg^{-1}		$cmol_c$ kg^{-1}	
Bayamón	424	84	492	22	6.4	6.1	9	0.09	5.6	6.8	13.1	52	0.6	0.05	62.8	6.5	1.6	4.2	45	–	335	174	0 ¶	7.0
Cecil eroded	420	174	406	70	5.8	5.4	2	0.07	1.5	2.8	8.5	33	2.8	0.04	27.8	2.6	2.1	4.3	41	–	333	138	0	7.5
Grey Clay	278	262	460	22	8.2	7.6	25	0.16	30.5	37.0	40.8	90	0.4	0.12	12.6	1.3	2.2	–§	104	0.063	323	201	1.5	9.2
Heiden	86	396	518	23	8.0	7.4	23	0.10	35.0	37.3	50.4	74	0.2	0.04	7.4	0.9	1.7	–	208	0.072	306	224	1.5	9.3
Hoytville	28	370	566	313	6.0	5.5	24	0.09	15.2	20.3	33.5	60	0.3	0.04	14.6	1.8	9.0	–	94	0.037	373	200	3.5	7.5
Irving clay	28	370	602	202	7.6	6.8	23	0.87	26.5	56.6	68.8	82	1.3	0.33	31.4	2.9	6.1	–	402	0.155	605	420	1.5	8.4
Londrina	63	275	662	378	5.6	5.0	16	0.04	3.0	6.4	21.0	30	0.2	0.01	156.5	5.2	7.1	4.0	101	–	309	237	0.5	5.7
Middle Ridge	147	389	464	197	5.8	5.1	27	0.08	6.6	9.5	29.5	32	0.3	0.02	108.8	4.6	5.0	4.0	119	–	276	197	1.0	5.6
Molokai	244	336	420	292	6.4	5.7	10	0.54	3.2	8.2	19.2	43	2.8	0.23	125.8	8.0	2.1	5.1	98	–	353	212	0.5	6.6
Pierre	422	276	302	208	7.2	6.4	17	0.15	12.3	18.2	24.7	73	0.6	0.08	11.2	1.1	2.2	–	110	0.048	224	134	2.5	8.5

† CDC, chemical dispersible clay; WDC, water dispersible clay; OC, organic ; TB, sum of basic cations; CEC, cation exchange capacity per gram of soil; BS, base saturation; ESP, exchangeable sodium percentage; SAR, sodium adsorption ratio; Fe_d, Fe extracted by DCB (dithionite-citrate-bicarbonate); Al_d, aluminum extracted by DCB; Fe_o, Fe extracted by ammonium oxalate; PZSE, point of zero salt effect; SA, surface area per gram of soil; COLE, coefficient of linear extensibility; θ_g, gravimetric water content; CFC, critical flocculation concentration of electrolytes.

‡ pH at flocculation.

§ Not determined.

¶ Flocculated without adding any electrolytes.

Table 3. Settling velocity for dry (V_{50D}) and wet (V_{50W}) aggregates of different sizes (<8, 4.76- to 8-, and 1- to 2-mm diam.), slaking index based on settling velocity (SI_V) based on settling velocity for aggregates 4.76 to 8.00 mm, interrill erodibility for wet (K_{iW}) and dry (K_{iD}) soil, and erodibility ratio (KR).

Soil Series	$V_{50D<8}$	$V_{50D1–2}$	$V_{50D4.76–8}$	$V_{50W4.76–8}$	SI_V ‡	K_{iW}	K_{iD}	KR§
	m s^{-1}					kg s m^{-4}		
Bayamón	0.06 cd†	0.04 c	0.40 a	0.40 a	1.00	1.30 x 10^6	0.60 x 10^6	2.17
Cecil eroded	0.12 bc	0.08 bc	0.23 b	0.35 ab	1.52	1.03 x 10^6	0.51 x 10^6	2.01
Grey Clay	0.06 cd	0.05 c	0.14 bc	0.14 cd	1.00	1.98 x 10^6	1.80 x 10^6	1.10
Heiden	0.28 a	0.25 a	0.40 a	0.29 b	0.73	0.78 x 10^6	0.43 x 10^6	1.81
Hoytville	0.30 a	0.20 a	0.40 a	0.40 a	1.00	1.09 x 10^6	0.64 x 10^6	1.70
Irving Clay	0.02 d	0.04 c	0.06 c	0.08 d	1.25	2.29 x 10^6	2.37 x 10^6	0.96
Londrina	0.06 cd	0.12 b	0.08 c	0.20 c	2.44	0.28 x 10^6	0.78 x 10^6	0.35
Middle Ridge	0.12 bc	0.12 a	0.37 a	0.37 ab	1.00	1.00 x 10^6	0.75 x 10^6	1.33
Molokai	0.12 bc	0.13 b	0.08 c	0.11 d	1.38	1.05 x 10^6	1.04 x 10^6	1.01
Pierre	0.18 b	0.24 a	0.40 a	0.40 a	1.00	0.35 x 10^6	0.33 x 10^6	1.06

† Means followed by the same letter are not significantly different (Tukey's test at α = 0.05).

‡$SI_V = V_{50W4.76–8}/V_{50D4.76–8}$.

§ $KR = K_{iW}/K_{iD}$.

Veejet nozzles (Spraying Systems, Wheaton IL). Deionized water with electrical conductivity (EC) < 18 μS cm^{-1} was used as rainwater, and the duration of the rain was 2 h for the most stable kaolinitic soils (Oxisols and Ultisols) and 1.5 h for the least stable smectitic and illitic soils (Alfisols, Aridisols, and Vertisols). These durations were sufficient to obtain steady-state conditions, as shown in Reichert and Norton (1994a, 1996), which were defined as the length of time when four consecutive runoff samples gave the same volume for the collection time. This of course took longer for the more stable soils.

Runoff and sediment were collected at the bottom edge of the pan. Steady-state (equilibrium) sediment loss rate was calculated as the averaged value for the last 10 min in each rain. Steady state rates are typically used to compare different soils since variability is minimized. Therefore, observed differences are real and not artifacts of preparation of the plot, for instance. Granted the slaking, swelling, and other processes occur in the non-steady state initial conditions, but there is a large amount of variability introduced when packing and prewetting.

Erosion trials were run twice in a completely randomized design. Analysis of variance (ANOVA), correlation analysis and stepwise multiple linear regressions were performed using SAS procedures. The multiple regression analysis had no predictive purpose, thus the coefficients are not presented. Means of the data were compared using the Tukey's multiple comparison test (α = 0.05) using SAS Institute (1988).

RESULTS AND DISCUSSION

Aggregate Settling Velocity and Slaking

The ranking of soils for settling velocity V_{50} (Table 3) and for MWD (Table 4) was dependent on the aggregate-size class and wetting conditions, demonstrating that the susceptibility to slaking is affected by those variables. In general, the V_{50} of dry aggregates in all soils was greater in the 4.76 to 8 mm compared with the other aggregate sizes (Table 3), in accordance with Lovell and Rose (1988b). The greatest V50 values of 4.76- to 8-mm aggregates are always 0.40 no matter what kind of soil types or pretreatments they are. The speed of which aggregates fall are a function of both size and mass. Because they are larger does not mean they fall faster nor have a greater density. Large aggregates with a lot of pore space may actually have a slower V_{50}. The least V_{50} of air-dried aggregates of three size-classes (<8 mm, 4.76–8 mm, and 1–2 mm) and prewetted aggregates (4.76–8 mm) was obtained for Irving Clay. This soil is highly expansive due to its smectitic clay, which increases clay dispersion and slaking on swelling, reducing the size of settling aggregates. Heiden and Pierre, although also smectitic, are less expansible (Reichert and Norton, 2004a), had high V_{50} and showed much higher

Table 4. Mean weight diameter by dry sieving (MWD_{DD}) and by wet sieving of prewetted (MWD_{WW}) and air-dry (MWD_{DW}) and aggregates of different classes, aggregate stability index (ASI) based on wet and dry sieving of aggregates < 8 mm, and slaking index based on aggregate stability (SI_{AS}) based on MWD from wet sieving of air-dry and prewetted aggregates of different classes.

Soil Series	$MWD_{DD<8}$	$MWD_{WW<8}$	$MWD_{WD<8}$	ASI‡	$SI_{AS<8}$§	$SI_{AS\,4.76–8}$¶	$MWD_{WW1–2}$	$MWD_{DW1–2}$	$SI_{AS\,1–2}$#
	mm						mm		
Bayamón	1.53 cd†	2.01 b	0.42 def	0.27	4.79	2.57	1.19 bc	0.33 e	3.61
Cecil eroded	1.77 cd	1.43 cb	0.34 ef	0.19	4.21	4.32	1.13 c	0.34 e	3.32
Grey Clay	1.20 cd	0.69 ed	0.25 f	0.21	2.76	2.88	0.66 e	0.23 f	2.87
Heiden	1.94 c	1.86 b	0.98 c	0.51	1.90	1.09	0.97 d	0.67 c	1.45
Hoytville	4.06a	3.69 a	2.32 a	0.57	1.59	1.07	1.32 a	0.51 d	2.59
Irving Clay	2.99 b	0.39 e	0.24 f	0.08	1.63	2.44	0.43 f	0.16 f	2.69
Londrina	1.24 cd	1.63 bc	0.53 de	0.43	3.08	4.69	1.4 a	0.68 c	2.06
Middle Ridge	1.09 d	1.32 bcd	0.57 d	0.52	2.32	2.95	1.28 ab	0.79 b	1.62
Molokai	1.98 c	1.12 cde	0.61 d	0.31	1.84	3.22	1.28 ab	0.80 b	1.60
Pierre	1.89 cd	1.97 b	1.72 b	0.91	1.15	1.09	1.36 a	0.99 a	1.37

† Means followed by the same letter are not significantly different (Tukey's test at α = 0.05).

‡$SAI = MWD_{DW<8}/MWD_{DD<8}$.

§$SI_{AS<8} = MWD_{WW<8}/MWD_{DW<8}$.

¶ $SI_{AS\,4.76–8} = MWD_{WW\,4.76–8}/MWD_{DW4.76–8}$ (data from Reichert and Norton, 1994b).

#$SI_{AS\,1–2} = MWD_{WW\,1–2}/MWD_{DW1–2}$.

aggregate stability by wet sieving (Table 4). On the other hand, the greatest V_{50} values varied among soils (Heiden, Hoytville, Pierre, and Bayamon) depending on the aggregate size evaluated; these four soils also had highest MWD for aggregates < 8 mm. Interestingly, no relation is observed between V_{50} and MWD of small-size aggregates (1–2 mm) when comparing soils, which reflected in a low or no correlation (Table 5).

The V_{50} for dry aggregates was positively correlated (Table 6) with critical flocculation concentration of electrolytes (CFC) and the ratio of CFC to clay content (CFC/%Clay) for aggregates < 8 mm and CFC/%Clay for 1- to 2-mm aggregates, whereas no correlation with soil properties was observed for 4.76- to 8-mm aggregates. A greater number of variables correlated with V_{50} for prewetted aggregates in the range of 4.76 to 8 mm, including water content at permanent wilting point, sodium adsorption ratio (SAR), and the ratio of SAR to clay content (SAR/%Clay). The V_{50} for <8-mm dry aggregates was significantly correlated (Table 5) with the V_{50} for dry aggregates of sizes 1 to 2 and 4.57 to 8 mm, and with the stability (MWD) of prewetted and initially dry aggregates < 8 mm.

As defined by Norton and Dontsova (1998), the slaking index (SI_V) represents the reduction (>1), increase (<1), or no effect (=1) in breakdown during settling due to capillary prewetting. Herein, SI_V refers to both differential swelling function by prewetting and the real slaking function induced by entrapped air during fast wetting. Four soils (three kaolinitic and one smectitic) had $SI_V > 1$, while for a silty clay smectitic soil this index was < 1 (Table 3). SI_V was significantly correlated with Fe content extracted by dithionite-citrate-bicarbonate, which represents crystalline pedogenic Fe forms, possibly through its positive effect on aggregate formation.

When testing aggregates 4.76 to 8 mm, soils with greater slaking index based on settling in water (SI_V) also had slower fall velocity of air-dry aggregates (V_{50D}) and greater slaking under wet sieving (SI_{AS}) (Tables 3 and 4). These are consistent results, since aggregate slaking causes a reduction in aggregate size and releases smaller aggregates that have slower fall velocity. However, when testing aggregate stability under wet sieving, the SI_{AS} expresses the increase in aggregate stability. Presumably, this is due to a decrease in slaking with capillary prewetting. Differences in slaking explain the tendency of greater stability under wet sieving for capillary-prewetted soil as compared to air-dried soil. Immersion of air-dried soil in water causes a pressure buildup of trapped air as water enters the intra-aggregate pores. If the rupture force overcomes the binding and cohesive forces holding particle together, then slaking occurs. Slaking is reduced with a reduced rate of wetting of aggregates, since no pressure builds up inside the aggregates while the surface tension of water holds particles together (Truman et al., 1990).

At the onset of a rainfall, the soil surface may be composed of large, dry aggregates that might not, however, resist the compressive and shearing forces from raindrop impact and runoff. An estimate of such a relation is given by the aggregate stability index (ASI), which is the ratio between the MWD of water stable aggregates to the MWD of dry aggregates (Table 4). A high value of ASI represents a small reduction in MWD diameter of aggregates of the bulk soil (<8-mm size aggregates) with wet sieving. The great-

Table 5. Pearson coefficient of correlation matrix for aggregate fall velocity (V_{50}), aggregate stability (MWD), slaking indexes, and interrill erodibility.

	$V_{50D<8}$	$V_{50D1–2}$	$V_{50D4.76–8}$	$V_{50W4.76–8}$	SI_V †	K_{iW}	K_{iD}	KR‡	$MWD_{DD<8}$	$MWD_{WW<8}$	$MWD_{DW<8}$	ASI§	$SI_{AS<8}$¶	$SI_{AS\,4.76–8}$#	$MWD_{WW1–2}$	$MWD_{DW1–2}$	$SI_{AS\,1–2}$††
$V_{50D<8}$	1																
$V_{50D1–2}$	0.87***	1															
$V_{50D4.76–8}$	0.65*	0.56	1														
$V_{50W4.76–8}$	0.51	0.43	0.91***	1													
SI_V 1	–0.44	–0.26	–0.65*	–0.33	1												
K_{iW}	–0.43	–0.69*	–0.36	–0.50	–0.32	1											
K_{iD}	–0.59	–0.63*	–0.70*	–0.80**	0.04	0.86**	1										
KR2	0.37	0.03	0.66*	0.63	–0.59	0.11	–0.41	1									
$MWD_{D<8D}$	0.46	0.19	0.07	0.01	–0.20	0.27	0.17	0.19	1								
$MWD_{W<8W}$	0.81**	0.78**	0.59	0.55	–0.29	–0.44	–0.49	0.12	0.57	1							
$MWD_{W<8D}$	0.75*	0.89	0.68*	0.72*	–0.16	–0.49	–0.67*	0.40	0.50	0.85**	1						
ASI3	0.56	0.81**	0.59	0.56	–0.20	–0.70*	–0.61	–0.11	-0.05	0.74*	0.50	1					
$SI_{MWD<8}$¶	–0.45	–0.60	0.00	0.21	0.26	0.05	–0.18	0.46	-0.41	–0.55	–0.07	–0.50	1				
$SI_{MWD4.76–8}$#	–0.67*	–0.62	–0.64*	–0.35	0.80**	–0.03	0.14	–0.31	-0.47	–0.70*	–0.46	–0.54	0.59	1			
$MWD_{W1–2W}$	0.36	0.49	0.40	0.60	0.27	–0.86**	–0.84**	0.03	-0.15	0.48	0.62	0.59	0.07	0.08	1		
$MWD_{W1–2D}$	0.43	0.75*	0.32	0.30	0.03	–0.82**	–0.62	–0.29	-0.25	0.47	0.28	0.80**	–0.46	-0.20	0.73*	1	
$SI_{MWD1–2}$ ††	–0.41	–0.72*	–0.09	0.07	0.06	0.52	0.24	0.48	0.14	–0.34	–0.01	–0.62	0.75*	0.31	0.40	-0.85**	1

†$SI_{V50} = V_{50W4.76–8}/V_{50D4.76–8}$.

‡$KR = K_{iW}/K_{iD}$.

§$ASI = MWD_{DW<8}/MWD_{DD<8}$.

¶ $SI_{AS<8} = MWD_{WW<8}/MWD_{DW<8}$.

$SI_{AS\,4.76–8} = MWD_{WW\,4.76–8}/MWD_{DW4.76–8}$ (data from Reichert and Norton, 1994b).

†† $SI_{AS1–2} = MWD_{WW1–2}/MWD_{DW1–2}$.

* $P < 0.05$.

** $P < 0.01$.

*** $P < 0.001$.

Table 6. Pearson coefficient of correlation for settling velocity of dry (V_{50D}) and wet (V_{50W}) aggregates of different sizes (<8-, 4.76- to 8-, and 1- to 2-mm diam.), slaking index based on settling velocity (SI_V) based on settling velocity for aggregates 4.76 to 8.00 mm, interrill erodibility for wet (K_{iW}) and dry (K_{iD}) soil, and erodibility ratio (KR) with selected soil properties.

Soil property	$V_{50D<8}$	V_{50D1-2}	$V_{50D4.76-8}$	$V_{50W4.76-8}$	SI_V †	K_{iW}	K_{iD}	KR‡
Sand	–0.208	–0.164	0.231	0.375	–0.151	–0.129	–0.344	0.386
Silt	0.484	0.496	–0.024	–0.243	–0.199	0.020	0.194	–0.342
Clay	–0.158	–0.241	–0.344	–0.351	0.442	0.186	0.352	–0.269
Water dispersible clay	0.043	0.219	–0.324	–0.175	0.584	–0.367	–0.008	–0.653 *
pH H_2O	0.040	0.062	–0.045	–0.378	–0.542	0.472	0.458	–0.037
pH $CaCl_2$	0.049	0.018	0.007	–0.316	–0.563	0.489	0.412	0.087
Organic	0.235	0.231	0.140	–0.129	–0.376	0.248	0.350	–0.298
Base saturation	0.108	0.066	0.030	–0.265	–0.566	0.533	0.493	–0.021
Cation exchange capacity (CEC)	0.047	0.021	–0.182	–0.484	–0.331	0.567	0.669*	–0.233
Fe oxalate	0.120	0.044	–0.129	–0.035	0.353	0.007	0.187	–0.350
Fe dithionite-citrate-bicarbonate	–0.436	–0.221	–0.424	–0.265	0.680*	–0.338	–0.056	–0.504
Critical flocculation concentration (CFC)	0.704*	0.574	0.364	0.223	–0.345	–0.017	–0.034	0.015
Surface area	–0.144	–0.082	–0.330	–0.549	–0.130	0.514	0.680*	–0.301
Permanent wilting point	–0.357	–0.344	–0.551	–0.695*	0.122	0.598	0.799**	–0.393
Field capacity	–0.351	–0.501	–0.518	–0.580	0.056	0.749**	0.784**	–0.096
Exchangeable Ca	0.246	0.159	0.046	–0.302	–0.534	0.471	0.441	0.011
Exchangeable Na	–0.381	–0.334	–0.597	–0.721*	–0.020	0.618	0.766**	–0.330
Exchangeable H+Al	0.182	0.251	0.048	–0.015	0.133	–0.211	–0.041	–0.276
Total bases	–0.007	–0.054	–0.204	–0.498	–0.379	0.651*	0.708*	–0.164
Exchangeable Na percentage (ESP)	–0.263	–0.207	–0.510	–0.522	0.076	0.215	0.282	–0.162
Sodium adsorption ratio (SAR)	–0.411	–0.376	–0.622	–0.753**	–0.061	0.669*	0.798**	–0.323
CFC/%Clay	0.721*	0.710*	0.462	0.324	–0.410	–0.171	–0.159	–0.038
SAR/%Clay	–0.354	–0.264	–0.583	–0.702*	–0.083	0.526	0.665*	–0.346

† $SI_V = V_{50W4.76-8}/V_{50D4.76-8}$.
‡KR = K_{iW}/K_{iD}.
* $P < 0.05$.
** $P < 0.01$.

est ASI was obtained for Pierre soil and the least ASI for Irving Clay. Soils with greater ASI had also faster fall velocity of 1- to 2-mm dry aggregates (V_{50D}) and aggregate stability of dry aggregates of the same size (MWD_W), and lesser interrill erodibility of prewetted soil (K_{iw}) (Table 3 and 4). This initially large, stable aggregates may resist the disrupting forces by raindrop impact and interrill overland flow, and thus explain the greater water infiltration rate and lower runoff rate observed by Reichert and Norton (1994a, 1996) and thus decreasing their erodibility of prewetted soil (r^2 = -0,71*, in Table 5) of those soils.

Aggregation Related to Soil Properties

The SI_{AS} (Table 4) expresses the increase (if > 1) or decrease (if < 1) in aggregate stability due to mainly a decrease in slaking during wet sieving of prewetted aggregates. For all the large aggregate sizes tested (<8 mm and 4.76–8 mm), the SI_{AS} was generally greatest for clayey soils rich in kaolinite and Fe and Al oxyhydroxides and least for 2:1 clay type silicates. Apparently, for the kaolinite and oxide dominant soils, the disruption of aggregates is mainly induced by slaking during fast wetting, not by differential swelling during pre-wetting.

The $SI_{AS<8}$ had a significant negative relation to silt, CFC, and CFC/%Clay, while $SI_{AS4.76-8}$ with base saturation, Fe extracted with dithionite-citrate-bicarbonate, CFC/%Clay. For the smaller aggregates (1–2 mm) no significant correlation was observed, whereas SI_{AS1-2} was negatively correlated with silt content.

Soils with a high silt content or high ratio of critical flocculation concentration to clay content rendered the soil unstable for both wetting conditions (initially dry and prewetted), indicating that the rate of wetting and thus slaking were not significantly reduced. Additionally, for soils with clay-sized silicates dominated by illite or smectite (with no kaolinite), the swelling of clays may have overridden any reduction in slaking by slow capillary prewetting, causing aggregate instability with both wetting procedures. Kemper et al. (1987) proposed that, in soils with high clay contents and surface area, interparticle contact and water adsorption increases the water tension for a given water content, but the hydration of exchangeable cations and swelling of clays weakens the bonds between soil colloids. In the Truman et al. (1990) study, differences in clay content and organic matter partially explained differences in stability with wetting.

The ranking of MWD of stable aggregates with wet sieving (Table 4) was dependent on soil aggregate size and wetting procedure, possibly indicating distinct action of aggregation agents and dispersion processes in aggregate stability. Correlation analyses for 1- to 2-mm prewet aggregates (MWD_W for 1- to 2-mm aggregates) showed the greatest number of properties with negative correlation (Table 7), namely pH in water and in $CaCl_2$, base saturation, CEC, surface area, water content at permanent

Table 7. Pearson coefficient of correlation for mean weight diameter by dry sieving (MWD_{DD}) and by wet sieving of prewetted (MWD_{WW}) and air-dry (MWD_{DW}) and aggregates of different classes, aggregate stability index (ASI) based on wet and dry sieving of aggregates < 8 mm, and slaking index based on aggregate stability (SI_{AS}) based on MWD from wet sieving of air-dry and prewetted aggregates of different classes with selected soil properties.

Soil property	$MWD_{DD<8}$	$MWD_{WW<8}$	$MWD_{WD<8}$	ASI†	$SI_{AS<8}$‡	$SI_{AS\ 4.76–8}$§	$MWD_{WW1–2}$	$MWD_{DW1–2}$	$SI_{AS\ 1–2}$¶
Sand	–0.485	–0.094	–0.150	0.156	0.488	0.121	0.206	0.043	0.309
Silt	0.444	0.091	0.385	0.203	–0.842**	–0.409	–0.110	0.314	0.667*
Clay	0.324	0.058	–0.151	–0.453	0.073	0.220	–0.217	–0.387	0.185
Water dispersible clay	0.315	0.248	0.369	0.260	–0.447	0.167	0.461	0.442	–0.406
pH H_2O	–0.004	–0.379	–0.094	–0.032	–0.356	–0.509	–0.728*	–0.250	–0.112
pH $CaCl_2$	–0.004	–0.326	–0.115	–0.093	–0.226	–0.495	–0.725*	–0.335	0.011
Organic	0.188	0.020	0.251	0.191	–0.614	–0.489	–0.320	0.047	–0.393
Base saturation	0.262	–0.156	0.145	0.049	–0.432	–0.642*	–0.694*	–0.326	0.013
Cation exchange capacity (CEC)	0.387	–0.298	–0.026	–0.175	–0.571	–0.441	–0.769**	–0.314	–0.183
Fe oxalate	0.583*	0.383	0.373	0.011	–0.305	0.010	0.104	–0.062	–0.016
Fe dithionite-citrate-bicarbonate	–0.385	–0.188	–0.346	–0.142	0.184	0.660*	0.458	0.344	–0.230
Critical flocculation concentration (CFC)	0.801**	0.634*	0.829**	0.411	–0.696*	–0.715*	0.046	0.148	–0.281
Surface area	0.360	–0.432	–0.162	–0.232	–0.505	–0.261	–0.723*	–0.277	–0.173
Permanent wilting point	0.380	–0.447	–0.312	–0.486	–0.312	0.004	–0.688*	–0.433	0.020
Field capacity	0.576	–0.339	–0.288	–0.643*	–0.113	0.033	–0.709*	–0.667*	0.363
Exchangeable Ca	0.225	–0.169	0.046	–0.077	–0.420	–0.569	–0.726*	–0.318	–0.113
Exchangeable Na	0.366	–0.547	–0.275	–0.393	–0.398	–0.044	–0.612	–0.283	–0.033
Exchangeable H+Al	0.143	0.116	0.114	0.090	–0.362	–0.003	0.217	0.363	–0.513
Total bases	0.362	–0.344	–0.061	–0.209	–0.488	–0.455	–0.862***	–0.433	–0.041
Exchangeable Na percentage (ESP)	0.114	–0.369	–0.228	–0.278	–0.156	0.167	–0.065	0.072	–0.103
Sodium adsorption ratio (SAR)	0.315	–0.585	–0.298	–0.407	–0.370	–0.045	–0.651*	–0.324	0.016
CFC/%Clay	0.635*	0.604	0.906***	0.671*	–0.783**	–0.799**	0.153	0.365	–0.438
SAR/%Clay	0.215	–0.556	–0.221	–0.252	–0.415	–0.066	–0.496	–0.136	–0.102

† ASI = $MWD_{DW<8}/MWD_{DD<8}$.

‡ $SI_{AS<8} = MWD_{WW<8}/MWD_{DW<8}$.

§ $SI_{AS\ 4.76–8} = MWD_{WW\ 4.76–8}/MWD_{DW4.76–8}$ (data from Reichert and Norton, 1994b).

¶ $SI_{AS\ 1–2} = MWD_{WW\ 1–2}/MWD_{DW1–2}$.

* $P < 0.05$.

** $P < 0.01$.

*** $P < 0.001$.

wilting point and at field capacity, exchangeable Ca, total bases, and sodium adsorption ratio. Zhang and Horn (2001) observed that the normalized mean weight diameter of the aggregates after fast wetting and wet stirring was more correlated with soil properties, such as degree of micro-aggregation, CEC, Fe and Al oxides rather than clay and soil organic content. All these results indicate that physical-chemical properties of the clay play an important role in aggregate stability of these soils with high clay content, as had been suggested previously by Warkentin (1982). Our present results also show that the relation between soil aggregate stability depends on aggregate size. When distinguishing between non-swelling (1:1 clay minerals and oxides) and swelling soils (2:1 clay minerals), Reichert and Norton (1994b) concluded that soil properties related to stability of 4.76- to 8-mm aggregates are quite different for the two groups of soils. They also observed that aggregate stability was positively related with CEC for non-swelling soils and negatively related for swelling soils, suggesting that for swelling soils increasing CEC may decrease aggregate stability due to increased cation hydration and swelling.

Aggregation Relation to Erodibility Parameters

For both prewet and air-dry soil, the interrill erodibility (K_i) was greatest for the smectitic Irving Clay, and the least for the kaolinitic Londrina and smectitic/illitic Pierre (Table 3). The low K_i for the Pierre soil was not expected, but possibly the presence of root fragments physically bound soil particles together, thus resisting soil detachment by rain impact and shallow overland flow.

Interrill erodibility, for initially dry soil (K_{iD}), was positively correlated (Table 6) with CEC, surface area, water content at permanent wilting point and at field capacity, exchangeable sodium, total bases, SAR, and SAR/%Clay. For prewetted soil, K_{iW} correlated to total bases, SAR, and water content at permanent field capacity.

Multiple regression analysis indicated that MWD_{WW} for prewetted 1- to 2-mm aggregates, available water content, and $V_{50D1–2}$ explained 89% of the variability in erodibility for prewet soil (K_{iW}), whereas MWD_{WW} for prewetted 1- to 2-mm aggregates, water dispersible clay, and V_{50D} for 1- to 2-mm aggregates explained 96% of the variability in erodibility for dry soil (K_{iD}). 97% of the variability in the K_i ratio (K_{iw}/K_{iD}) was explained by the soil properties ΔpH (pH_{H2O}- pH_{CaCl2}), SI_V, and surface charge (cation exchange capacity/surface area). These results are in agreement with observations of Warkentin (1982) and Reichert and Norton (1994b) that stability, and thus interrill erodibility, of soils with high clay content depends on the physical-chemical properties of the clay.

Interestingly, interrill erodibility had a higher correlation (Table 5) with the stability (MWD) of aggregates in the 1- to 2-mm size class, than for the whole soil (aggregates < 8 mm), contrary to the suggestion of DeBoodt et al. (1974) that correlations between aggregate stability and soil loss may sometimes exist only if the whole soil is tested. This demonstrates a need for further studies. No significant correlation, however, was observed with any of the slaking indexes involving for wet sieving (SI_{AS}) or settling in water (SI_V) for these high clay soils in the interrill erodibility.

The increased aggregate stability and settling velocity observed with capillary prewetting, in general, did not result in lesser erodibility, possibly because of the high water table kept during rainfall on the prewetted soil. Prewetting from the bottom up increased interrill erodibilty for eight soils, and decreased it for two soils with the highest clay content (Londrina and Irving Clay), regardless of the clay mineralogy. This result is contrary to the observed by Truman and Bradford (1990) who obtained a lesser wash loss for prewetted than for air-dried soil only for the Heiden clay soil, but are in concordance with the observations of Francis and Cruse (1983). As the matric potential increases and approaches a zero potential (close to saturation), a decrease in both the soil aggregate strength (Benjamin and Cruse, 1985) and aggregate stability (Francis and Cruse, 1983) can be expected. As the pores become saturated, swelling of clays generates pressure and cohesion is reduced, thus increasing aggregate instability. These authors state that soil management practices, which enhance internal drainage and promote reductions in the matric potential in the plow layer, will promote structural stability, while slow drainage will have the opposite effect.

These apparent contradictory results demonstrate the importance of the drainage condition. In our study, for the dry soil water drained freely, while for the prewetted soil the water table was kept at −0.5-kPa matric potential below the soil surface. Under this situation, the capillary fringe extended even closer to soil surface, maintaining the soil close to saturation, possibly reducing soil strength and aggregate stability, thus increasing the soil erodibility. Although, keeping the soil at a −0.5-kPa matric potential throughout the rain is desirable when infiltration is measured implicitly and a uniform tension among soils is of interest (Reichert and Norton, 1994b), such low tension rarely takes place in the field (Sharma et al., 1981). Additionally, prewetted soil with near surface water table increased steady-state runoff for four kaolinitic soils compared with initially air-dry soil with free drainage, namely Bayamón, Cecil, Middle Ridge, and Molokai, while no statistical difference was observed for the other six soils (Reichert and Norton, 1994b).

There appears to be a confounding effect of a high water table, high steady-state runoff, and slaking may explain the greater erodibility and lack of slaking reduction effect on our prewetted soil under simulated rainfall. One way to resolve this is to apply different rates of wetting and similar tensions in the soil, at least after a surface seal has formed. Also, shearing forces during wet sieving and settling in water are vastly different in magnitude from the shearing and compressive forces under raindrop impact with a high intensity rainfall. These suggest that an alternative method of aggregate stability testing, such as using raindrop impact (Young, 1984; Reichert et al., 1992; Loch and Foley, 1994), be considered in erosion studies.

CONCLUSIONS

The results of this study confirm that the soil clay properties affect aggregate settling velocity and stability and soil interrill erodibility. The slaking index based on aggregate stability, for all the large aggregate sizes (<8 mm and 4.76–8 mm), was generally greatest for clayey soils rich in kaolinite and Fe and Al oxy-hydroxides and least for 2:1 clay type silicates, demonstrating a decrease in slaking during wet sieving of prewetted aggregates of the former soils. For the kaolinite and oxide dominant soils, the disruption of aggregates is mainly induced by slaking during fast wetting, not by differential swelling during prewetting. Highly smectitic clay increases particle dispersion and slaking on swelling, thus reducing the size and speed of settling aggregates. For soils with clay-sized silicates dominated by illite or smectite (with no kaolinite), the swelling of clays may have overridden any reduction in slaking by slow capillary prewetting, thus causing aggregate instability with both slow and fast wetting procedures. In the absence of rooting effect on aggregation, the interrill erodibility (K_i) was greatest for the highly smectitic and least for the high-clay kaolinitic/oxidic soil. In the correlation and regression analysis, soils with 4.76- to 8-mm aggregates with greater slaking index (SI_V) while settling in water had also greater slaking under wet sieving (SI_{AS}) and slower fall velocity (V_{50D}). Interrill erodibility of dry and wet soil had a greater correlation with the stability (MWD) of aggregates in the 1- to 2-mm size class, than for the whole soil (aggregates < 8 mm), while no correlation was observed with any of the slaking indexes involving wet sieving (SI_{AS}) or settling in water (SI_V). Multiple regression analysis indicated that MWD_{WW} for 1- to 2-mm prewetted aggregates, available water content, and V_{50D} for 1- to 2-mm aggregates explained 89% of the variability in erodibility for prewet soil (K_{iW}), while MWD_{WW} for 1- to 2-mm prewetted aggregates, water dispersible clay, and V_{50D} for 1- to 2-mm aggregates explained 96% of the variability in erodibility for dry soil (K_{iD}). Correlations of aggregate stability and fall velocity with soil properties suggest that physical-chemical properties of the clay fraction play an important role in aggregate stability of these soils with high clay content. A confounding effect of high water table, steady-state runoff and slaking explain the greater erodibility and lack of slaking reduction effect on our prewetted soil under simulated rainfall. When comparing the two tested methods to determine aggregate stability, our method based on settling velocity generated direct information on aggregate slaking, sediment transportability, and speed of deposition, which are directly related to soil erosion and sedimentation.

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